Applied Energy 211 (2018) 346–357

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Impact of room temperature on energy consumption of household refrigerators: Lessons from analysis of field and laboratory data

Lloyd Harrington, Lu Aye*, Bob Fuller

Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Vic 3010, Australia

HIGHLIGHTS

- Measured performance of 111 laboratory & 235 home refrigerators is analysed.
- The effect of room temperature on energy consumption is investigated.
- Repeatable effects are found for different types of refrigerators.
- Universal empirical relationships for estimating energy consumption are developed.
- Approach allows modelling the effects of room temperature with minimal data input.

ARTICLE INFO

Keywords:
Household refrigeration
Refrigerators
Freezers
Energy consumption
Room temperature
Modelling energy

ABSTRACT

Refrigerators are a common appliance in developed and emerging economies around the world. These appliances consume significant energy globally and improving their efficiency is an important aspect of future climate change mitigation. It is widely understood that the energy consumption of household refrigerating appliances is strongly influenced by room temperature and many analysts have identified ambient temperature as the most important factor in normal use. Room temperature has two main effects on the energy consumption of refrigerating appliances. Firstly, the temperature difference between the compartment and the room dictates the heat gain into the appliance through the wall insulation and door seals. A second effect is that a change in room temperature affects the condensing temperature. An increase in room temperature reduces overall refrigeration system efficiency by increasing the difference between the evaporating and condensing temperature. This paper examines laboratory data for 111 appliances where energy consumption is measured at four ambient temperatures from 10 °C to 40 °C. Field data for 235 appliances in homes is also examined. This is more complex to analyse, but it does provide useful information on underlying energy changes due to changes in room temperature during normal use. This paper determines the ratio of energy at 16–32 °C (energy conditions in IEC62552-3) and explores the shape of the energy curve at intermediate temperatures in order to develop a generalised energy curve as a function of temperature for the refrigerating appliances measured. The field data gave highly comparable shape data to that measured in the laboratory. The results provide a useful method to estimate the likely power consumption of different appliance types under a wide range of operating conditions, even where limited data is available.

1. Introduction

Refrigerators are ubiquitous appliances, with most households in developed countries having at least one, while there is rapid growth in ownership in developing countries [1,2]. Global sales of new refrigerators is around 150 million units a year [3,4] and the global stock in 2009 was estimated to be around 1.6 billion household refrigerating appliances [5]. These appliances are estimated to consume as much as 6% of global electricity [6] and improving their efficiency is an important aspect of future climate change mitigation. An important first step in the development of suitable energy policies to reduce energy consumption is the understanding of key drivers of energy consumption.

The vast majority of refrigerating appliances in service globally use the vapour compression cycle as this is the lowest cost and most efficient technology currently available for these appliances [7]. While it is

* Corresponding author.
E-mail address: lua@unimelb.edu.au (L. Aye).

https://doi.org/10.1016/j.apenergy.2017.11.060
Received 15 July 2017; Received in revised form 6 November 2017; Accepted 10 November 2017
Available online 18 December 2017
0306-2619/ Crown Copyright © 2017 Published by Elsevier Ltd. All rights reserved.

widely understood that the energy consumption of household refrigerating appliances is strongly influenced by room temperature, there is little data or analysis into the impacts that changes in room temperature have on the energy consumption of these appliances, especially during normal use. Early research into refrigerator energy consumption identified that ambient temperature was a key driver of energy consumption [8–12]. This has been confirmed in many recent studies, which conclude that room temperature in which the appliance operates is the most important factor that impacts on energy consumption in conditions of normal use [13–20]. The main research question to be addressed is how can the changes in energy consumption of refrigerating appliances that are likely to be experienced under conditions of normal use be estimated from existing data sets and measurements without the need for extensive testing and complex additional measurements.

One possible approach is simulation. The literature has many examples of simulation of the energy consumption of household [14,21–26] and many of these models can estimate the energy consumption of a specific refrigerator in different ambient temperatures [27–29]. However, these simulation models are generally intended for use by engineers to improve and optimise the overall design of household refrigerators and the components that they use. These models require a lot of detailed engineering information about the design and construction of each appliance and its components and they use complex numerical approaches such as Computational Fluid Dynamics. The level of information required is not readily available and much of it is certainly not in the public domain. These types of models, while absolutely essential for product design and optimisation, have limited applicability in the development of broader energy policies and are generally not suitable for the estimation of energy consumption during normal use.

Test procedures are also another possible source of information. Until recently, most test procedures around the world for refrigerating appliances only measured energy of refrigerating appliances at a single ambient temperature. In the past, many test procedures specified an elevated room temperature for energy determination in order to compensate for the lack of user interactions during the test [8,10]. This means that reliable and accurate energy consumption data at different ambient temperatures is very limited globally. While refrigerators are a thermally dynamic appliance, documenting generic responses to changes in room temperature has not been undertaken previously in a way that can inform policy makers and analysts to help them understand how the energy consumption of these appliances varies in the field. In 2015, the International Electrotechnical Commission (IEC) Standard IEC62552-3 was published [30]; it set out a new global approach to energy consumption measurement, including energy tests at 16 °C and 32 °C. The pool of available data should expand as countries adopt the new IEC test method.

At this stage there is still a paucity of laboratory data on how refrigerating appliances typically respond to room temperature; this aspect of energy consumption is rarely published by suppliers as there is no obligation to do so under programs like energy labelling. Around the world there have been many campaigns that measure the energy consumption of refrigerating appliances during normal use in homes and offices. However, this data is complex because changes in energy consumption in response to room temperature, additional energy due to user interactions and additional energy associated with automatic defrosting are all mixed up together [31–35]. These types of studies in the past have been unable to explicitly take into account and separate the impact of changes in room temperature at each site.

Refrigerators are the most commonly regulated product for energy efficiency of any appliance or piece of equipment, with some 75 countries having 185 separate program measures for these appliances in 2013 [36]. The shortcomings in historical test procedures means that products are often measured and rated at conditions that are far from normal use. Therefore, products may be optimised for operating conditions that do not reflect normal use and the estimated energy consumption from test procedures is usually inadequate for estimating energy costs for consumers and energy saving potential.

Detailed analysis of data from compressor manufacturers reveals that the change in the coefficient of performance (COP) for most products is very linear with changes in condenser temperature, as expected. However, an unexpected finding is that the absolute slope of COP for most compressors is very similar, regardless of the rated COP. This means that real compressor COP does not strictly follow theoretical Carnot COP for changes in condensing temperature. This is valuable background to understanding the analysis results in this paper.

There is a lack of information in the public domain that sets out the likely response of household refrigerating appliances to changes in room temperature, even though there is widespread understanding that the energy consumption of these appliances is sensitive to room temperature. This is a critical gap in the current knowledge as this type of information is important for the development of sound energy policies and it is crucial for forecasting energy demand into the future. The findings documented in this paper will provide a robust technical basis for making improvements to energy policies such as energy labelling and minimum energy performance standards, as well as providing a more credible basis for converting data measured in a test laboratory into more realistic estimates of energy consumption in the field. This will assist in energy forecasts and projections as well as large scale modelling of the energy consumed by these appliances into the future.

The aim of this paper is to provide a clear understanding of how refrigerating appliances operate across a range of temperature conditions that are likely to be encountered in normal use. This is achieved by examining the steady state power consumption as a function of room temperature for a wide range of refrigerating appliances both in the laboratory and in homes to provide rigorous generic relationships between temperature and power consumption for a wide range of product types. Previous studies have only covered a limited number of appliances, types and operating conditions and have not provided generic functions of the impact of temperature on energy across a large temperature range. Analysis in this paper provides confidence that the behaviour of many refrigerating appliances is consistent and can be generalised, which is an important expansion of our understanding of their energy consumption during normal use. The paper also provides practical tools to translate the energy consumption measured under different test procedures to a more generic function of steady state power versus ambient temperature for most normal use conditions. It therefore provides policy makers and analysts with a set of quantitative tools that could lead to improvements in policy development and energy forecasts, even where limited data is available, which would lead to improved energy efficiency and reduced energy consumption during normal use. It is based on measured data for a large number of appliances in the laboratory and in homes, which provides a unique insight into the energy consumption of refrigerators across a wide range of room temperatures.

2. Theory

2.1. Heat transfer into a refrigerating appliance

The heat gain through the walls of a refrigerator (including all sides exposed to ambient air and door seals) is a function of the insulation effectiveness (thermal transmittance or U value), surface area and the overall temperature difference between the internal compartment temperature and the room air temperature surrounding the refrigerator. When considering a specific refrigerator, the U value and the surface area are both fixed at the time of design and manufacture, so the heat gain through the appliance walls into each compartment is a linear function of the temperature difference (external temperature minus internal temperature). Often there are several compartments, each with a different U value and each with a different operating temperature that

Break out box 1
Why is the slope of compressor COP similar for all compressor efficiency levels?

An idealised compressor efficiency follows Carnot, which is defined as the low temperature (in K) divided by the temperature differential (between the condenser and the evaporator). At ASHRAE rating conditions, Carnot COP is about 3.1 $W \cdot W^{-1}$. Real compressors have much lower COP than Carnot COP (between 0.3 and 0.75 of the Carnot COP – see Fig. 2). A common simplified approach to adjusting the COP of real compressors is to assume that the compressor COP remains at a fixed percentage of Carnot COP over the expected operating range of condenser temperatures. However, the data in Fig. 2 shows that this is not the case – the slope of real compressors appears to be fairly constant in absolute terms, irrespective of the rated COP. There are a number of reasons why real compressor efficiency is lower that the theoretical value:

- A reciprocating compressor uses a piston to compress the refrigerant in vapour state - in practical terms, this must have some clearance at the end of its stroke, so not all of the refrigerant vapour in the cylinder can be pushed out. The ratio of the displaced volume to the total volume is called the volumetric efficiency. The impact of this clearance depends on the suction pressure and the discharge pressure, but this is a major factor that influences compressor COP.
- During operation there are other factors that reduce the efficiency of real compressors: there is friction between the piston and the cylinder during pumping; there may be leakage of refrigerant around the piston, there is heating of the refrigerant gas suction gas which reduces volumetric efficiency; there will be pressure drops across suction and discharge valves.

These factors will mean that real compressors have relatively moderate efficiency compared to the theoretical maximum. The linear response to changes in condensing temperature and the relatively constant slope of real compressor COP suggests that once the losses and inefficiencies are overcome, then their incremental efficiency is closer to that found in an ideal gas compressor. This is likely to explain why the slope of small real reciprocating compressors that are used in refrigerators (irrespective of their rated COP) produce a fairly constant change in COP with changes in condensing temperature. This is useful to know when modelling the energy consumption of refrigerator under different room temperatures.

is fairly constant. In this case, the total heat gain through the walls is still linear as a linear function for each compartment sums to produce an overall linear function for the whole appliance. Therefore, heat gain through the walls can always be considered to be linear with a change in room temperature, assuming the overall U value is constant. Where there are multiple compartments, only the external surface area for each compartment should be considered (as internal heat flows between compartments do not affect the overall heat gain into the cabinet). However, there are other sources of heat gain that need to be considered, such internal fans, internal heaters and energy dissipated from electronics, which will all be largely unrelated to changes in room temperature.

2.2. Efficiency of a refrigerating appliance

The COP of the refrigeration system in an appliance is measured as the ratio of the heat absorbed in the evaporator (mass flow rate of refrigerant times the enthalpy difference of the refrigerant entering the evaporator at a defined evaporating temperature and entering the compressor at ambient temperature) and the input power of the compressor. Rating bodies like the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) and Comité Européen des Constructeurs de Matériel Frigorifique (European Committee of Manufacturers of Refrigeration Equipment or CECOMAF) rate compressors at fairly extreme operating conditions, such as a condensing temperature of +55 °C, as this reflects the hottest likely practical operating condition for households. A compressor that can meet this requirement in terms of cooling capacity will comfortably meet the cooling requirements under normal operating conditions, which sometimes includes cooling warm food and drink.

The compressor efficiency at rated conditions does not provide an understanding of how the energy consumption of an appliance may be affected by changes in room temperature. Once a refrigerator has been designed and constructed, the evaporator will usually operate (more or less) within a narrow range of design temperatures. There may be exceptions to this general rule (e.g. products that use multiple evaporators or that have complex refrigeration configurations), but most mainstream products use a single evaporator, which itself has a single evaporating temperature. When the compressor is operating in a steady state condition, the evaporating temperature is typically 5–10 K colder than the coldest compartment temperature [37], but this temperature differential may be as large as 20 K in some cases as the evaporator has to be colder than the compartment to provide a net cooling effect. As compartments are designed to operate within a relatively narrow temperature range, the evaporator will also operate within a narrow temperature range when the compressor is operating.

To understand the changes in energy consumption during use, it is important to obtain information about how the refrigeration system energy efficiency will change under a range of typical operating conditions. The most obvious consideration is that the room temperature around the refrigerator will influence the condensing temperature. Typically, the condenser, which is used to reject heat from the working fluid (refrigerant) to the ambient environment, will be somewhat warmer than the surrounding air. The temperature difference depends on the type of condenser, but typically this would be in the range 5–10 K warmer than the room air temperature [38–40] when the compressor is operating in steady state conditions. Most refrigerators would spend most of their operating life in room temperatures in the range of 10–35 °C, which could include condensing temperatures ranging from 15 °C to 45 °C, which is significantly cooler than rated conditions.

One of the primary effects on the refrigeration system of increased condensing temperature is an increase in the pressure ratio against which the compressor has to work, which results in a decrease of both volumetric efficiency and mass flow rate of refrigerant. The next important effect is that an increased temperature of liquid leaving the condenser (at the inlet to the evaporator) reduces the available refrigerating effect from the boiling refrigerant as it leaves the expansion device. For reciprocating compressors, the type used in most household refrigerators, a change in the condensing temperature has a (more or less) linear effect on the compressor COP. This is also stated in number of academic text books [41]. This linear relationship between condensing temperature and COP is supported by published compressor performance data provided by a range of compressor manufacturers, but this is somewhat different to the idealised Carnot COP response (see Break out box below). Published data from a single compressor Model EG AS70HLP is illustrated in Fig. 1 [42]. Note the strong effect of evaporating temperature on compressor COP.

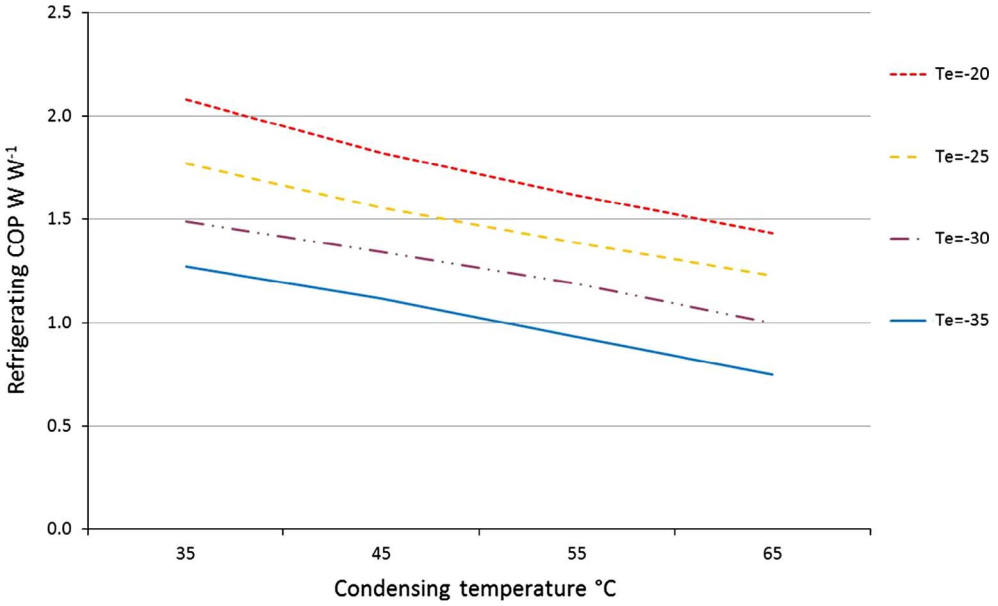

Fig. 1. Effect of condensing temperature on COP for different evaporating temperatures for Embraco Model EG AS70HLP.
Data source: Embraco data sheets [42].

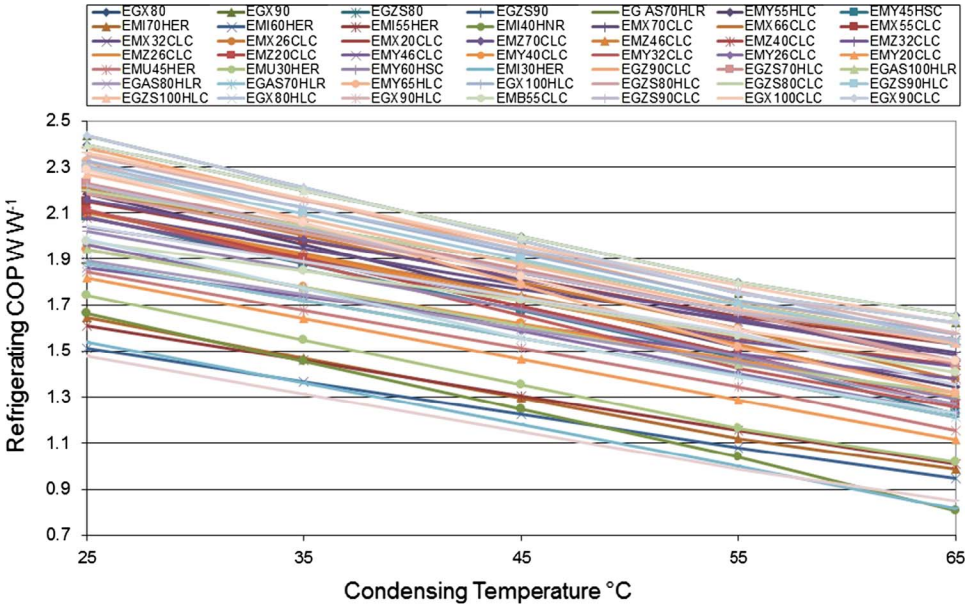

Fig. 2. Effect of condensing temperature on COP for 49 compressors – ASHRAE ratings.
Data source: Embraco data sheets [43].

A review of data for many compressors from several manufacturers suggests that the response of COP to changes in condensing temperature is linear (as expected) and the slope (COP K^{-1}) is almost constant for various capacities and COP ratings across different compressors. There is no obvious difference between compressors using refrigerants R600a and R134a in terms of linearity. The ASHRAE rating suggests a COP slope, on average, of about -0.018 per K change in condensing temperature while the CECOMAF rating suggests a COP slope on average of about -0.03 per K change in condensing temperature (the difference being the sub-cooling of condensed fluid in the ASHRAE rating system). Data for ASHRAE ratings for 49 compressors is shown in Fig. 2. While there is some variation between compressors, the average slope is remarkably consistent for all compressor models, even where rated COP is very different. Some 40 of the 49 models shown have a slope that lies in the range -0.015 COP K^{-1} to -0.021 COP K^{-1}. This means that most compressors should respond to changes in condensing temperature at a similar rate of COP change per K.

2.3. Expected response of refrigerators to changes in room temperature

Room temperature has two main effects on the energy consumption of refrigerating appliances. Firstly, the temperature difference between compartment temperatures and the room temperature dictates the heat gain into the appliance through the cabinet wall insulation and door seals. A second effect is that a change in room temperature affects the condensing temperature. An increase in room temperature reduces overall refrigerating system COP by increasing the difference between the evaporating and condensing temperature. As noted previously, there are also usually fixed or variable heat loads (such as heaters, fans and controls) that are not related to room temperature.

Changes in heat gain through walls and door seals are linear and in proportion to the temperature difference between the room temperature and the compartment temperature(s). The COP of the compressor and the refrigeration system is expected to decrease linearly as the room temperature increases. A linear increase in heat gain and a linear decrease in COP with increasing room temperature results in a refrigerator energy response to changes in room temperature that is a

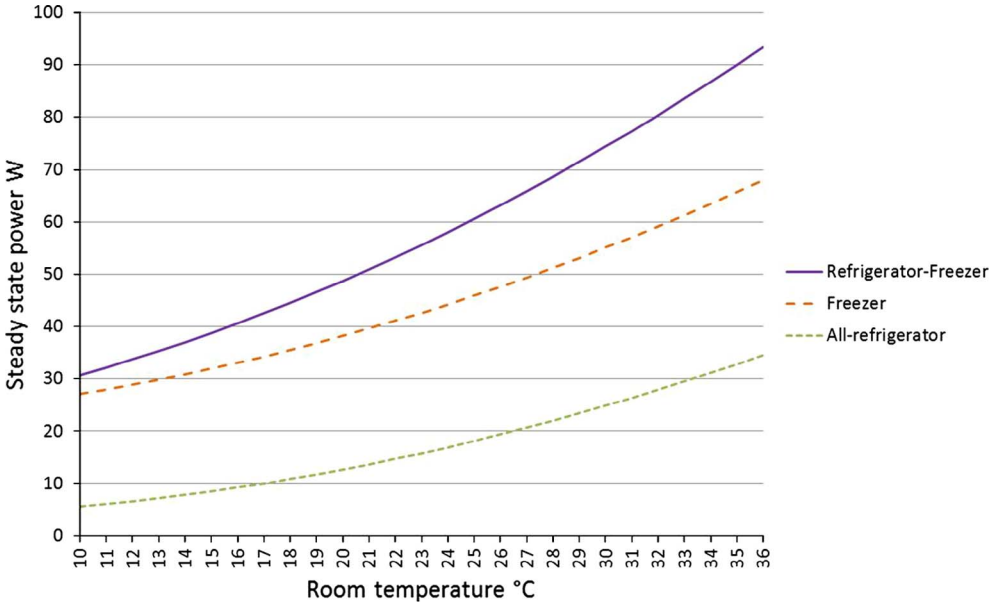

Fig. 3. Changes in steady state power in response room temperature for three refrigerating appliances.
Data source: Australian Consumers' Association [44] and authors' analysis.

curve. Fig. 3 illustrates laboratory measured data for three appliances measured at four different room temperatures [44]. As expected, the result is a gentle curve. Note that this is steady state power consumption with no defrost or user interaction. It is important to note that the rated cooling capacity of refrigeration systems greatly exceeds the cooling requirement under most operating conditions, so most appliances (even those with inverter driven compressors) will cycle on and off in order to match the cooling output of the refrigeration system with the cooling requirement to maintain stable compartment temperatures. In this paper, the steady state power for a cycling appliance is calculated as the average power over a whole compressor cycle where there is no additional load from user interactions or defrosting.

3. Method

To examine the effect of room temperature on energy consumption of refrigerating appliances, two main data sets were used. The first data set was routine laboratory tests conducted over a period of five years by the Australian Consumers' Association and covers 111 different models of different product types and configurations [44]. Products were measured in an accredited test laboratory at four test temperatures: 10 °C, 20 °C, 32 °C and 40 °C over a period of typically around one week. For these tests the appliances were fully instrumented with multiple compartment temperature sensors and data collected at 1 min intervals in accordance with AS/NZS4474.1 [45].

The second data set was the measured energy consumption of refrigerating appliances in homes during normal use collected by the authors. Data for 235 appliances was recorded for periods ranging from a few months to over a year. High quality energy data was collected at an equivalent of 1 min intervals. Room temperature data was also collected.

3.1. Laboratory data analysis

The laboratory data was analysed using traditional refrigerator test method techniques by splitting the data into compressor cycles and examining the steady state power for each compressor cycle at a specific temperature [30,45]. The representative steady state power after stabilisation was determined from the data at each of the relevant test room temperatures. A quadratic equation was then fitted to the points across the four temperatures [46] in order to give a generalised function of expected steady state power versus room temperature for the individual appliance model. The resulting equation was checked at each of the four temperature points to verify that the fitted value was within 1 W of the measured data. After review of the data of the original 129 models, it was found that some of the data could not be used for the following reasons:

- Some missing data or issues with the laboratory measurements (5 units)
- Behaviour or design of the appliance that was not conducive to automated analysis (e.g. very large ambient compensation heaters > 10 W, dual compressors, multiple defrost systems, faulty appliances, circumvention devices present, erratic inverter system) (10 units)
- Poor fit of the quadratic equation (3 units).

This left 111 models of the original 129 models in the laboratory data set that were available for full analysis. A total of 68 of these had an ambient response curve that was acceptable, the appliance had no ambient compensation heater and the compartment temperatures were stable across all ambient temperatures without adjusting the temperature controls. The remaining 43 models were classified separately into two further sub-categories as set out below.

As the room temperature decreases (say below 15 °C), the heat gain into the fresh food compartment of a refrigerator-freezer becomes very low due to the small temperature difference. However, the heat gain into the freezer is still significant, so some cooling is still required. If the appliance is unable to automatically modulate or independently control cooling into each compartment, then one of two approaches is typically taken. The first approach is to turn on a small compensation heater in the fresh food compartment to allow the freezer to be cooled while maintaining the fresh food temperature above freezing. This also helps to stop cold air stratification in the fresh food compartment. The second approach is to maintain only the fresh food temperature within an acceptable range while allowing the freezer compartment temperature to rise in the lower room temperature, thus reducing the cooling requirement, which results in reduced compressor run time and appliance energy consumption. In this design of product, which is typically based on a mechanical control, the temperature balance between the fresh food and freezer compartment is not automatically maintained in low ambient temperatures, so without active user adjustment of temperature controls, it can result in freezer temperatures that are too warm. Users may not be not aware of these changes in the freezer temperature,

which could be an issue if such warming occurred on a regular basis.

A total of 18 models appeared to have small low ambient compensation heaters that operated at lower room temperatures (typically below 22 °C) with a heater power typically in the range 2–6 W (all less than 10 W). These were all refrigerator-freezers. The curve fit for these models was generally quite good (all with an R^2 of > 0.99), but the measured steady state power at a room temperature of 10 °C was often equal to or higher than the power at 20 °C. When operating, these compensation heaters effectively increase the steady state power consumption because some of the electrical energy is directed to a compartment heater and this additional energy also has to be removed by the refrigeration system, thus reducing overall COP. This increases the apparent curvature of the temperature-power line by pushing up the power at lower room temperatures.

A total of 22 models had significant temperature drift at lower room temperatures (a higher freezer temperature for this analysis is defined as more than 2 K warmer than for other room temperatures). These were all refrigerator-freezers. Note that the way the units were tested meant that no appliance temperature control changes were made as the test room temperature changed. For these products, it is almost certain that a different compartment control setting could have achieved a suitable freezer temperature and fresh food temperature combination. The Australian Standard, which all locally supplied appliances must meet prior to sale [45], requires at least one control setting in ambient temperatures of 10 °C, 32 °C and 43 °C where temperature requirements in all compartments can be satisfied during a storage test. A higher freezer temperature at lower room temperatures results in a curve that is somewhat straighter than otherwise expected (lower power at lower room temperatures) as the relative heat gain into the freezer is reduced as the freezer temperature rises.

Having a quadratic curve for each individual model allowed the change in slope to be examined across different test temperatures (by examining the first differential of power with respect to temperature) and the steady state power to be calculated at 16 °C from the fitted curve. This test temperature is of some interest as the new IEC62552-3 standard specifies energy consumption measurements at 16 °C and 32 °C.

3.2. Field data analysis

In a test laboratory, appliances have instrumentation measuring a range of parameters such as power and compartment temperatures. When measuring data in homes, the number of parameters that can be collected is quite limited. For the 235 refrigerators and freezers monitored in homes, power data was collected each minute and a representative room temperature was also measured. This allows compressor cycles to be separately identified and their length and average power calculated as per laboratory data. The data can then be plotted with room temperature on the horizontal axis and average compressor cycle power on the vertical axis. An example is provided in Fig. 4 for a refrigerator-freezer (unit ID RF0031) located in Gippsland, Victoria based on data collected by the authors. The lower boundary of this data (shown as a continuous line) is effectively the change in steady state power in response to changes in room temperature. A method to disaggregate the energy measurements of refrigerators in homes into the key components is set out in several recent studies [47–49].

This type of graph has been prepared for each of the 235 appliances that have been measured in homes. This provides a useful comparison to the laboratory data. For data measured in homes, there are some limitations. It is generally very difficult to record internal compartment temperatures in the field, so there is no information on whether the compartment temperatures drift with changes in room temperature. For some appliances it is likely that compartment temperatures may drift as the room temperature changes, but the net effect depends on the individual appliance. However, the approach used takes into account changes in energy consumption as well as any natural compartment temperature drift that may occur under different room temperatures (without control changes), so it a reasonable representation of the overall response to temperature, which is the key objective in this paper. Another factor is that users may adjust compartment temperature controls from time to time and this will effectively push the lower boundary up or down by several watts. These are detected by plotting the lower boundary power vs time and the actual average compressor power vs time. If the lower boundary curve is correct, it will nestle into the shape of the actual average power over a period of days or weeks as most appliances generally recover to stable conditions overnight where there is normally little residual user interaction. If there are extended periods where the actual average power is above or below the lower boundary line, then this indicates that the user has changed the temperature control setting. The method allows for the lower boundary curve to be adjusted up or down by a few watts to compensate for different user control settings throughout the monitoring period. This process effectively creates a family of lower boundaries, one for each control setting that applies to a specific subset of the monitoring period. The method includes the net average effect of control changes over the measurement period. A quadratic equation was fitted to the lower boundary and included a weighted average correction to take account of user adjustment of temperature controls. In contrast to laboratory measurements, which are generally measured over a week or so, most field measurements are measured over periods ranging from three months to a year. In homes, the room temperature is constantly changing and there is also significant impact resulting from user interactions.

3.3. Product classification

Because the laboratory tests and field data were collected on a wide range of different product types and configurations, it is useful to collect similar products together for analysis. A convenient categorisation of products is the Group as defined in AS/NZS4474.1 and as set out in Table 1.

4. Results and discussion

4.1. Laboratory data results

As there are data for 111 models, it is not possible to present data for each model individually. Individual models were organised into Groups as defined in AS/NZS4474.1 and as set out in Table 1. This allowed key parameters to be calculated for similar product types. As noted previously, some additional sub-categories were added for products where low ambient compensation heaters were present and for products where freezer temperatures drifted significantly at a room temperature of 10 °C. These sub-categories are somewhat general and individual products may vary in their behaviour. For example, ambient compensation heaters vary in power and the conditions in which they are activated differs by model. The heater power and activation temperature does have an effect on the shape of the curve, so data for these products should be used with caution. Similarly, the freezer temperature for some products drifted around 2 K while others drifted as much as 6 K – this will clearly have some effect on the shape of the curve. The key results of the analysis are presented in Table 2.

4.2. Laboratory data discussion

There are many points of interest in this data. The main parameters are illustrated in Fig. 5. Despite the variations in power consumption at different temperatures, most refrigerators and freezers follow a predictable change in power consumption across different temperatures. While there is some variability at a model level, the standard deviation of the ratio P_{16}/P_{32} ratio for each grouping is generally less than 4% indicating fairly consistent behaviour within each Group. At a

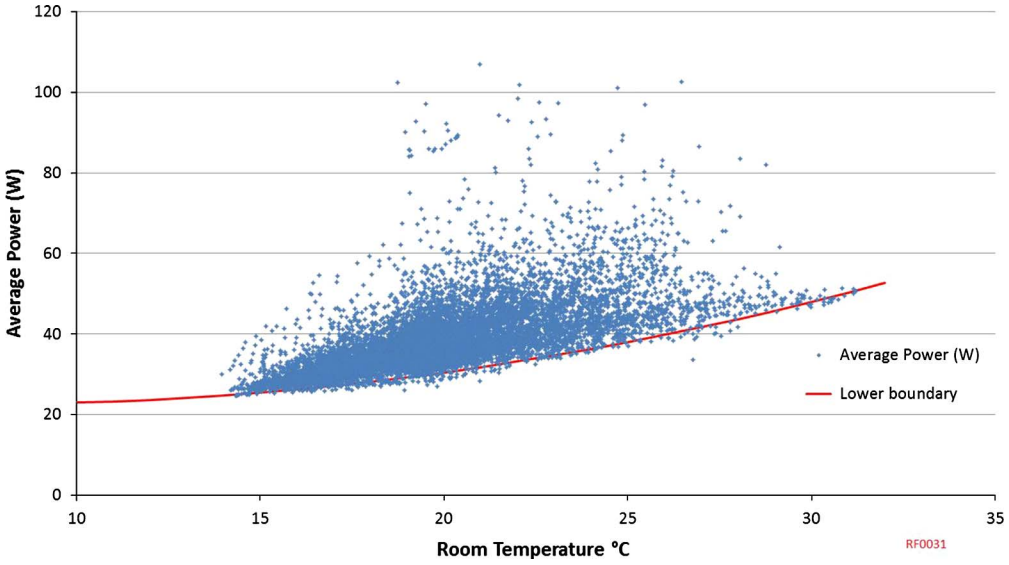

Fig. 4. Fitting a curve to the lower edge of compressor cycle average power (excludes defrost and recovery).

Table 1
Refrigerator and freezer Groups as defined in AS/NZS4474.1.

Group	Configuration
1	Refrigerator without a low temperature compartment, automatic defrost (fresh food compartment only, single door)
2	Refrigerator with or without an ice making compartment, manual defrost (bar fridges, single door)
3	Refrigerator with a short-term frozen food compartment, manual defrost (single door)
4	Refrigerator-freezer, fresh food compartment is cyclic defrost, freezer is manual defrost
5T	Refrigerator-freezer, both compartments automatic defrost, top mounted freezer
5B	Refrigerator-freezer, both compartments automatic defrost, bottom mounted freezer (includes French doors)
5S	Refrigerator-freezer, both compartments automatic defrost, side-by-side
6C	Chest freezer, all defrost types (usually manual defrost)
6U	Vertical freezer, manual defrost
7	Vertical freezer, automatic defrost

Notes: For Groups 2 and 3, the low temperature compartment is usually an internal sub-compartment. Descriptions in brackets are common configurations. Source [45].

temperature of 16 °C, refrigerator-freezers tend to use about 45% of the power at 32 °C, while freezers use about 50% of the power. At a temperature of 16 °C, all refrigerators (Group 1), with no low temperature compartment, are very strongly affected by a reduction in room temperature, and use about 31% of the power they use at 32 °C. This data shows that measurement of a refrigerator or freezer at a single temperature has no hope of reflecting the likely energy consumption during normal use due to the significant differences between types of products and the wide range of room temperatures encountered in normal use.

For those appliances with a smooth response to room temperature (i.e. those without low ambient compensation heaters or without warmer freezers), all showed a similar degree of non-linearity in the curve, at around about 5–6.5% at a room temperature of 24 °C. The exception was all refrigerators, which had a significantly stronger non-linearity at 8.7%. The other characteristic of interest is the slope of the power curve at each temperature. At a temperature of 16 °C, refrigerator-freezers had a slope of about 5% while freezers had a slope of just under 4%. All refrigerators had a much steeper slope of 9.3%. At a temperature of 32 °C, refrigerator-freezers and freezers had a slope of 4–5%, even for those products with low ambient compensation heaters or with warmer freezers, probably because those effects were absent at that temperature. All refrigerators had a slope of 5.7%.

For all appliances tested in the laboratory, data was available on the surface area of each compartment and an approximate insulation thickness. This allowed the overall thermal transmittance and external surface area (U.A) for each compartment to be calculated. Using actual compartment temperatures, it was possible to estimate the overall COP of the refrigeration system at a room temperature of 32 °C. A similar calculation was undertaken at a temperature of 16 °C. This calculation showed that the change in COP between a room of 32 °C and 16 °C was, on average, −0.02/K across the 44 Group 5T and 5B models with smooth data. This is very close to the slope predicted from the analysis of compressor map data for ASHRAE ratings (see Figs. 1 and 2).

These calculations were also performed at a temperature of 10 °C in order to calculate the COP based on the estimated heat gain and the measured power value. This data showed that the estimated COP at 10 °C was worse than the estimated COP at 16 °C for most models, with an average change in COP of −0.08. According to an extrapolation of the expected linear change in COP with a change in condensing temperature, an improvement of COP of +0.012 from 16 °C to 10 °C is expected. This suggests that the system COP is falling off quickly as room temperatures fall below 20 °C. The COP under these low ambient conditions might even be expected to increase as the average condensing temperature difference declines as run-times decrease in low room temperatures. This shows that the slope of the power curve, as measured at lower room temperatures, is flatter than would be expected from a standard model of heat gain and COP.

The decline in COP in colder room temperatures is an area where limited research has been undertaken because few energy tests are conducted at these temperatures and products are not generally rated under these conditions. For refrigerators and freezers that use a single speed compressor or an inverter that is cycling, it would appear that refrigeration system start-up losses contribute to this apparent fall in COP [23,50,51]. At low room temperatures, run times become very short, with compressor 'on' times of typically less than 10 min in a compressor cycle length of 40 min or more.

Where there are no internal barriers restricting the movement of refrigerant, which is typical in household refrigerators as most designs use capillary tubes [52], it will migrate to the coldest point (the evaporator) and condense when the compressor is 'off' [53–55]. When the compressor next starts, the refrigerant mass flow rate is initially higher due to the suction gas pressure being relatively high and condenser back pressure low. The compressor power is a function of both mass flow rate and pressure difference across it. The condenser back pressure rises quite quickly but the mass flow rate drops relatively slowly as it is proportional to the fall in evaporating temperature. Refrigeration does not reach its full capacity until there is enough condensed refrigerant to

Table 2
Key power parameters for different product configurations – laboratory data.

Group	Power 16 °C (W)	Power 32 °C (W)	Ratio P_{16}/P_{32} (%)	Std Dev P_{16}/P_{32} (%)	Slope @ 16 °C (%WK^{-1})	Slope @ 32 °C (%WK^{-1})	Non-linearity 24 °C (W)	Non-linearity 24 °C (%)	Model Count	Notes
1	10.3	33.0	31.5	3.4	9.3	5.7	1.9	8.7	4	All refrigerator
5T	26.3	57.4	45.4	4.5	5.0	4.6	2.8	6.7	23	Smooth
5T	25.0	52.6	47.7	3.9	2.9	5.1	4.0	10.4	9	Low ambient heaters
5T	19.8	52.0	37.8	3.1	7.3	5.1	2.5	6.8	19	Warmer freezer at 10 °C
5B	28.7	63.0	45.4	2.9	5.5	4.3	2.4	5.1	21	Smooth
5B	33.5	64.4	52.2	1.8	3.7	4.0	2.8	5.7	9	Low ambient heaters
5B	25.9	60.7	42.7	1.5	6.7	4.3	1.8	4.2	3	Warmer freezer at 10 °C
5S	38.3	79.1	48.3	3.1	4.9	4.1	2.8	4.8	13	Smooth
6C	20.3	40.7	50.0	4.1	3.9	4.3	2.0	6.4	6	Smooth
6U	16.2	34.0	47.6	#N/A	3.6	4.8	2.2	8.8	1	Smooth, only 1 model
7	28.6	54.7	51.5	4.4	3.6	4.1	2.6	6.4	3	Smooth

Notes: A total of 111 products are included. Only one Group 6U product was measured so data for Group 6U needs to be treated with caution. Power values are steady state and exclude defrosts and any user interaction. Low ambient heaters generally operated at room temperatures of less than 22 °C, but this varied by model. Readers should exercise caution when using the data for appliances with low ambient heaters as the response to changes in room temperature is dependent on the heater power and activation profile in the specific appliance. Source: authors' analysis of [44]. Standard Deviation is calculated on the ratio of P_{16}/P_{32} for all relevant products in the grouping. Non-linearity is a measure of the difference between a linear response between 16 °C and 32 °C (average of these values at 24 °C) minus the actual estimated power from the steady state curve – see Fig. 5. Percentage slope can be converted back to an absolute slope in W K^{-1} by multiplying %W K^{-1} by the linear W at the room temperature. While the relative slope at 16 °C is higher for most products, the absolute slope is much smaller due to the lower power. For example, the slope for Group 5S at 16 °C is 1.9 W K^{-1} (4.9%) while at 32 °C it is 3.2 W K^{-1} (4.1%). Percentage slope provides a more consistent basis for comparing data across different product types.

continuously supply liquid into the capillary or expansion valve. An excellent description of the refrigerant migration during cycling is provided in Björk and Palm [14,56].

This effect is obvious where evaporator temperatures are monitored, as illustrated in Fig. 6. In this example, the compressor turns on at 75 s and the evaporator surface temperature is –12.9 °C. It takes 135 s of compressor operation for the evaporator to reach its stable operating temperature of −22.4 °C. Given that the evaporator temperature change is linear during this period, a reasonable estimate would be that about half of this compressor operating time and energy input is effectively doing no work – this equates to about 2.5 Wh of refrigeration system start-up losses in this case. Some of this loss can be recouped after the compressor turns 'off' as evaporation will continue while there is a supply of condensed refrigerant at the capillary or expansion valve. However, this only provides cooling where the fan on a remote evaporator continues to operate for several minutes after the compressor switches 'off'.

The example in Fig. 6 is at a test room temperature of 32 °C and the energy for the whole compressor cycle is 26.6 W h, meaning that the start-up loss is less than 10% in this case. When operating at 10 °C, the start losses could be as much as 30% due to the very short compressor 'on' time.

Several authors found that the optimum charge of refrigerant increases at lower ambient temperatures [14,57]. This seems to be explained by a slower redistribution process and by more refrigerant held up in the compressor oil at lower ambient temperatures, both increasing the optimum charge. Another factor that may explain the apparent decline in COP at low room temperatures is incomplete condensation. This may occur due to the higher refrigerant flow rates at lower condensing temperatures. Any gaseous refrigerant that is able to pass through the expansion device will provide no cooling effect in the evaporator and will reduce effective COP, although the share of vapour

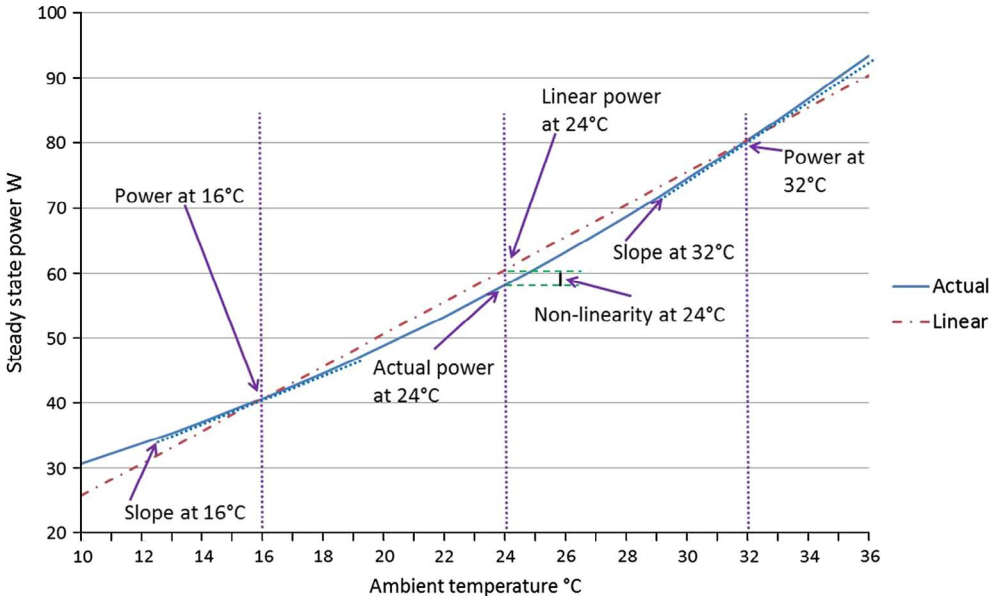

Fig. 5. Illustration of key parameters set out in Table 2.

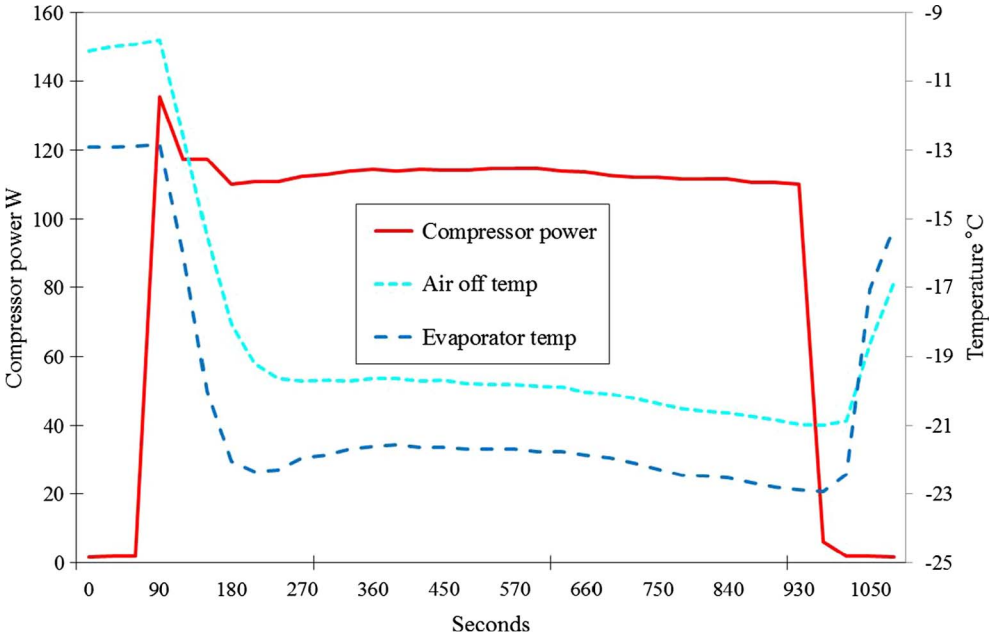

Fig. 6. Data for a household refrigerator showing power and evaporator temperatures.

able to pass through capillary tubes in terms of mass flow rate is likely to be small (estimated to be one quarter by [54]). Design engineers are aware that this can be an issue but it is very hard to quantify this occurrence in an operating product [58]. As more testing is conducted at lower temperatures and as regulators start to use these energy measurements for rating purposes, manufacturers will have an incentive to optimise the efficiency of their products at lower room temperatures. One approach that is likely to be very effective is the use of variable speed compressors, where the refrigerant flow rate can be reduced in lower room temperatures to better match the refrigeration capacity required. This also results in lower temperature gradients on the evaporator and condenser as well as less on-off cycling that will reduce start-up losses.

4.3. Field data results

There is complete data for 235 models from field data, so individual models were organised into Groups and then key parameters were calculated, as per the laboratory data. For Group 2 and Group 3, only three models were measured in the field, so these results have not been discussed in detail. As compartment temperatures were not measured during field data collection, it was not possible to identify products with a higher temperature freezer in low room temperatures. However, products with ambient compensation heaters could be identified. The key results are presented in Table 3.

4.4. Field data discussion

The data in Table 3 has the same column headings as Table 2 to allow direct comparison of data. The first point to note when comparing the laboratory data to the field data is that all of the laboratory appliances were new whereas the field data was a mixture of old and new refrigerating appliances, which is more representative of the installed stock. Quite a few of the appliances were over 20 years old. Because of this, the steady state power consumption of field appliances was considerably higher than the laboratory appliances at the same room temperature for the same Group. Older appliances may suffer from deterioration in insulation and gaskets seals and some deterioration in compressor performance, although these effects appear to be modest in the sample (obviously faulty appliances were excluded from the analysis). Newer refrigerators are also much more efficient than older refrigerators at their time of manufacturer [59,60]. This is likely to affect the temperature response characteristics of these appliances to some extent.

The other consideration is that, while most appliances were measured for very long periods (typically three to 12 months), the indoor temperature conditions may not have covered the whole range of interest in this analysis (i.e. 16–32 °C). For example, houses in Cairns in tropical Queensland rarely fell below 20 °C in winter and houses in Melbourne rarely rose above 28 °C in summer. This means that the values estimated at 16 °C and 32 °C had to be extrapolated for some appliances, which is necessarily less precise. The final point to consider is that appliances in homes are subject to user interactions and the temperatures in homes are continually changing. These factors generate more variability in the field data, which in turn reduces accuracy to some extent when compared to laboratory data. Some appliances in the field were very old and a few were operating sub-optimally, so this also leads to more variable results. Despite these caveats, the field data provides a lot of valuable information on the performance and behaviour of refrigerating appliances.

Overall, the data on the shape of power curves derived from field measurements is highly comparable to that derived from laboratory measurements. Generally, the ratio of power at 16–32 °C was similar for field measurements and laboratory measurements on similar products, which suggests that this data can be used to characterise the temperature performance of refrigerating appliances in more general terms using fairly limited data, even for older products with different energy consumption. The variability of the field data in terms of the standard deviation of the ratio of P_{16}/P_{32} was generally around double that for the laboratory data, but this is expected given the wide age range and the inclusion of some appliances with deteriorating performance. Freezers appeared to behave almost identically in the laboratory and in the field, despite the wide range of sizes, ages and energy consumption across the models measured. Refrigerator-freezers in the field appeared to have a lower slope at 16 °C and higher non-linearity at 24 °C when compared to equivalent laboratory products. This may be a function of absolute energy consumption and product design, where these products appear to be less efficient at lower temperatures. Some older Group 5T and 5B appliances used a cyclic defrost system in the fresh food compartment, which generally used an ‘off’ cycle heater. These types of heaters are always ‘on’ when the compressor is ‘off’ and so are not identified as ambient compensation heaters in the above analysis, but

Table 3
Key power parameters for different product configurations – field data.

Group	Power 16 °C (W)	Power 32 °C (W)	Ratio P_{16}/P_{32} (%)	Slope @ 16 °C (% WK^{-1})	Slope @ 32 °C (% WK^{-1})	Non-linearity 24 °C (W)	Non-linearity 24 °C (%)	Model Count	Notes
1	23.5	60.2	39.0	5.9	5.5	4.5	10.5	15	All refrigerator
2	14.7	24.2	60.5	2.3	4.0	1.2	7.1	2	One small, one large
3	44.9	71.5	62.8	1.2	3.9	4.5	7.7	1	Extremely old
4	62.0	116.9	53.0	1.9	4.7	8.9	9.7	9	No lab data
5T	38.1	85.8	44.4	4.9	5.1	5.9	8.9	46	Smooth
5T	31.0	64.8	47.8	3.3	4.8	4.4	8.9	12	Low ambient heaters
5B	43.5	90.0	48.4	3.3	4.9	6.1	9.2	49	Smooth
5B	37.8	73.1	51.7	3.2	4.4	4.1	7.4	35	Low ambient heaters
5S	50.6	92.8	54.6	2.8	4.0	5.0	6.8	31	–
6C	37.4	71.3	52.4	3.7	4.0	3.0	5.4	15	–
6U	38.5	79.8	48.3	3.1	4.9	5.6	9.3	13	–
7	46.2	86.3	53.6	2.7	4.3	4.7	7.6	7	–

Notes: A total of 235 products are included. Only one Group 3 and two Group 2 products were measured so this data needs to be treated with caution. General notes from Table 2 also apply to this table. Power values are steady state and exclude defrosts and any user interaction. Low ambient heaters generally operated at room temperatures of less than 22 °C, but this varied by model. Readers should exercise caution when using the data for appliances with low ambient heaters as the response to changes in room temperature is dependent on the heater power and activation profile in the specific appliance. Products with freezer temperature drift could not be identified in field data in Group 5T and 5B. Source: authors' analysis of field data collected by the authors. Non-linearity is a measure of the difference between a linear response between 16 °C and 32 °C (average of these values) minus the actual estimated power from the steady state curve – see Fig. 5.

they effectively act as a partial ambient compensation heater in practice. However, they may increase the non-linearity at 24 °C and slope at 16 °C, which may explain most of the small differences between laboratory measurements and field measurements. The slope at 32 °C is highly comparable for laboratory and field measurements for all product types.

4.5. General application of results

To make this data more useful, values from the laboratory quadratic equations for a range of relevant ambient temperatures have been generated and included in Table 4. This data will facilitate in the conversion of energy data from a range of common test procedures currently in use in different regions where energy consumption is determined at a single room temperature. Where energy consumption is determined at two ambient temperatures, for example in the new IEC test method [30], the measured energy ratio should be used together with the percentage non-linearity for the product type in Table 2 in order to generate a characteristic curve.

The data presented in Tables 2 and 3 allows a curve to be developed of steady state power as a function of ambient temperature for refrigerators even where very little energy data is known. If an energy value is only known at an ambient temperature of 32 °C for a specific type of product, the energy at 16 °C can be estimated using the relevant ratio in the tables provided. This then allows the energy to be estimated at a temperature of 24 °C using the non-linearity properties for each type of product. Alternatively, data from Table 4 can be used to generate a generic curve where a single energy consumption value is only known for one of the listed ambient temperatures. Any three of the values in Table 4 can be used to generate a unique quadratic equation to cover all temperatures in the range 10 °C to 35 °C.

Table 4
Ratio of power for each category of refrigerator for different ambient temperatures using power at 32 °C as a base.

Group	P_{16}/P_{32} (%)	P_{20}/P_{32} (%)	P_{24}/P_{32} (%)	P_{25}/P_{32} (%)	P_{30}/P_{32} (%)	Notes
1	31.5%	44.6%	60.3%	64.6%	89.0%	All refrigerator
5T	45.4%	55.7%	68.1%	71.6%	91.2%	Smooth
5T	47.7%	55.3%	66.4%	69.8%	90.2%	Low ambient heaters
5T	37.8%	49.8%	64.2%	68.2%	90.2%	Warmer freezer at 10 °C
5B	45.4%	56.3%	69.1%	72.5%	91.6%	Smooth
5B	52.2%	61.2%	72.0%	75.1%	92.2%	Low ambient heaters
5B	42.7%	55.0%	68.6%	72.2%	91.6%	Warmer freezer at 10 °C
5S	48.3%	58.8%	70.8%	74.1%	92.1%	Smooth
6C	50.0%	59.0%	70.3%	73.5%	91.7%	Smooth
6U	47.6%	56.5%	68.0%	71.3%	90.8%	Smooth, only 1 model
7	51.5%	60.4%	71.4%	74.4%	92.0%	Smooth

For example, a new frost free refrigerator-freezer with a bottom freezer (Group 5B) is known to have a steady state power of 65 W in a room temperature of 32 °C. The expected ratio of power for 16 °C/32 °C is 45.4% from Table 2, which gives an estimate of the power at 16 °C of 29.51 W. The expected power at 24 °C for a linear response is the average of the value at 32 °C and 16 °C, which equates to 47.26 W. For this type of product, the non-linearity at 24 °C is estimated to be 5.1%, which equates to 2.41 W. Therefore, the estimated power consumption at 24 °C is 47.26 W minus 2.41 W = 44.84 W. This provides three unique combinations of temperature and power consumption, and from this data it is fairly easy to fit a unique quadratic equation to this data using a spreadsheet, an equation solver [46] or manual solution of simultaneous equations. In this case the power at any given temperature is given by: $P = 0.038T^2 + 0.405T + 13.44$, where P is the expected power at a given ambient temperature and T is the ambient temperature in degrees Celsius.

An alternative approach is to use the value of P_{24}/P_{32} directly from Table 4 to calculate the power as 65 W times 0.691 which equals 44.9 W. Power values at 20 °C, 25 °C and 30 °C can also be calculated from Table 4 as required.

This approach provides a robust estimate of the steady state power consumption of the appliance under a wide range of different operating conditions using very little input data. However, care is required if examining temperatures outside of the range 10–35 °C as the fitted curve may not be valid, especially where non-linearity is large. All of the analysis in this paper has been conducted on steady state power measurements without the effect of defrosts or user interactions. Many test procedures record the energy consumption in a way that includes the net impact of one or more defrost and recovery events. Ideally, the incremental impact of these defrost events should be subtracted from the data before the method is applied. It is possible to estimate the incremental impact of a defrost and recovery event from measurements performed under the IEC62552-3 Annex C [30]. Several papers have also documented how the incremental defrost and recovery energy can be estimated from laboratory and field data [49,61].

Detailed analysis has shown that the share of defrost energy in

homes in Australia remains relatively constant across different room temperatures and climates [47], so inclusion of defrost energy may still provide a reasonable result when adjusting for different room temperatures. Steady state power or energy per period (day, month, year) can be used in this analysis, but the important consideration is to ensure units remain consistent in the calculations.

5. Conclusions

The analysis in this paper investigates the energy response to changes in room temperature of a wide range of refrigerating appliances that were measured in a test laboratory and in homes. While the overall method used for analysis of the two data sets is similar, the two data sets are completely independent and the conditions of operation are completely different, yet the results are highly comparable. While the characteristics of individual products in the two data sets varied widely, analysis showed that each type of product showed broadly similar responses to changes in room temperature. This provides a high level of confidence that the data and the analysis in this paper are sound. While there were some small differences in the measured parameters determined in the laboratory and in the field, these are mostly likely explained by the differences in age, design and energy consumption of field appliances, which were older and used more energy when compared to the new products measured in the laboratory under the same conditions.

The key parameters determined in this paper provide important insights into how refrigerating appliances operate under different ambient conditions. This data is valuable as it allows analysts to make reasonable estimates of the likely energy consumption of different refrigerating appliances under different operating conditions, even where very limited data is available, such as the energy consumption at a single temperature. The analysis also shows that all types of refrigerating appliances are broadly similar in their behaviour with respect to the non-linearity of the power curve in response to changes in room temperature.

More in-depth analysis revealed that the apparent COP of most appliances declines at low room temperatures. This is an area that has historically received little attention from appliance designers because few products are measured and rated at low ambient temperatures under programs like energy labelling and efficiency standards. This is somewhat ironic, as most appliances in developed countries spend most of their operating life at these cooler temperatures [62] and very little time at the elevated temperatures used in many test procedures. A significant proportion of the total energy consumed during normal use, therefore, is at lower ambient temperatures where appliance efficiency tends to be lower than expected. The rapid uptake of the new IEC62552-3 test method in many regions means that energy data at a temperature of 16 °C should become more readily available in future. Once this test method is more widely used in rating systems, such as energy labelling, the focus of designers will be on the optimisation of energy efficiency at lower room temperatures. This should result in the more rapid deployment of technologies such as compressors with variable speed drives to improve low temperature performance and the elimination of ambient compensation heaters.

Acknowledgements

The authors gratefully acknowledge the supply of laboratory data by the Australian Consumers' Association for the purpose of research and development work at the University of Melbourne. The authors also acknowledge the supply of field measurements for 39 appliances by Sustainability Victoria for the purpose of research and development work at the University of Melbourne. The authors would also like to acknowledge Fisher & Paykel Appliances in New Zealand for the supply of selected research and development laboratory data and for advice on refrigerator design, construction and operation [58] and to Ian McGill and Lindsey Roke of the refrigeration division for their helpful comments on this paper.

References

[1] McNeil MA, Letschert V, de la Rue du Can S. Global potential of energy efficiency standards and labeling programs. Berkeley, California: Ernest Orlando Lawrence Berkeley National Laboratory; 2008. p. 138.
[2] Rao ND, Ummel K. White goods for white people? Drivers of electric appliance growth in emerging economies. Energy Res Soc Sci 2017;27:106–16.
[3] Euromonitor International Ltd. Passport global market information database. London (United Kingdom): Euromonitor International Ltd; 2017.
[4] GfK Marketing. Major domestic appliances – world market estimation. Nuremberg (Germany): GfK Retail and Technology GmbH; 2017.
[5] Consultants Klinckenberg. Global carbon impacts of energy using products. Netherlands: Meersen; 2009.
[6] Negrão COR, Hermes CJL. Energy and cost savings in household refrigerating appliances: a simulation-based design approach. Appl Energy 2011;88:3051–60.
[7] Bansal PK, Vineyard E, Abdelaziz O. Advances in household appliances – a review. Appl Therm Eng 2011;31:13.
[8] Alissi MS, Ramadhyani S, Schoenhals RJ. Effects of ambient temperature, ambient humidity, and door openings on energy consumption of a household refrigerator-freezer. ASHRAE Trans 1988;94:1714–36.
[9] Goodson MP, Bullard CW. Refrigerator/freezer system modeling. Air Conditioning and Refrigeration Center, University of Illinois at Urbana-Champaign; 1994.
[10] Grimes JW, Mulroy W, Shomaker BL. Effect of usage conditions on refrigerator-freezer and freezer energy consumption. ASHRAE Trans 1977;83(Part 1).
[11] Koa JY, Kelly GE. Factors affecting the energy consumption of two refrigerator-freezers. ASHRAE Trans 1996;102(Part 2).
[12] Meier AK, Heinemeier K. Energy use of household refrigerators: a comparison of laboratory and field use. ASHRAE Trans 1988;94:1737–44.
[13] Anjana HMK, Nimarshana PHV, Attalage RA. Steady state performance variation of domestic refrigerators under different ambient conditions of Sri Lanka. MERCon 2015 – Moratuwa engineering research conference; 2015. p. 177–81.
[14] Björk E, Palm B. Performance of a domestic refrigerator under influence of varied expansion device capacity, refrigerant charge and ambient temperature. Int J Refrig 2006;29:789–98.
[15] Geppert J, Stamminger R. Analysis of effecting factors on domestic refrigerators' energy consumption in use. Energy Convers Manage 2013;76:794–800.
[16] Hermes CJL, Melo C. Assessment of the energy performance of household refrigerators via dynamic simulation. Appl Therm Eng 2009;29:1153–65.
[17] Hermes CJL, Melo C, Knabben FT, Gonçalves JM. Prediction of the energy consumption of household refrigerators and freezers via steady-state simulation. Appl Energy 2009;86:1311–9.
[18] Saidur R, Masjuki HH, Choudhury IA. Role of ambient temperature, door opening, thermostat setting position and their combined effect on refrigerator-freezer energy consumption. Energy Convers Manage 2002;43:845–54.
[19] Saidur R, Masjuki HH, Eow KF, Jamaluddi MY. Actual usage conditions and energy consumption of refrigerator-freezers. Int Energy J 2006;7:103–24.
[20] Saidur R, Masjuki HH, Hasanuzzaman M, Kai GS. Investigation of energy performance and usage behavior of domestic refrigerator freezer using clustering and segmentation. J Appl Sci 2008;8:3957–62.
[21] Borges BN, Hermes CJL, Gonçalves JM, Melo C. Transient simulation of household refrigerators: a semi-empirical quasi-steady approach. Appl Energy 2011;88:748–54.
[22] Borges BN, Melo C, Hermes CJL. Transient simulation of a two-door frost-free refrigerator subjected to periodic door opening and evaporator frosting. Appl Energy 2015;147:386–95.
[23] Heimel M, Berger E, Posch S, Stupnik A, Hopfgartner J, Almbauer R. Transient cycle simulation of domestic appliances and experimental validation. Int J Refrig 2016;69:28–41.
[24] Mastrullo R, Mauro AW, Menna L, Palma A, Vanoli GP. Transient model of a vertical freezer with door openings and defrost effects. Appl Energy 2014;121:38–50.
[25] Mitishita RS, Barreira EM, Negrão COR, Hermes CJL. Thermoeconomic design and optimization of frost-free refrigerators. Appl Therm Eng 2013;50:1376–85.
[26] Negrão COR, Erthal RH, Andrade DEV, Silva LWD. A semi-empirical model for the unsteady-state simulation of reciprocating compressors for household refrigeration applications. Appl Therm Eng 2011;31:1114–24.
[27] Sakallı Ö, Kerpiççi H, Kuddusi L. A study on optimizing the energy consumption of a cold storage cabinet. Appl Therm Eng 2017;112:424–30.
[28] Gupta JK, Ram Gopal M, Chakraborty S. Modeling of a domestic frost-free refrigerator. Int J Refrig 2007;30:311–22.
[29] Zhang L, Fujinawa T, Saikawa M. Theoretical study on a frost-free household refrigerator-freezer. Int J Refrig 2016;62:60–71.
[30] IEC62552-3. Household refrigerating appliances – characteristics and test methods - Part 3: Energy consumption and volume. Geneva: International Electrotechnical Commission; 2015.
[31] Greenblatt J, Hopkins A, Letschert V, Blasnik M. Energy use of US residential refrigerators and freezers: function derivation based on household and climate characteristics. Energ Effic 2012;6:28.
[32] JEMA. Refrigerator market monitoring project – 2008: Refrigerator monitoring survey report. Tokyo: The Japan Electrical Manufacturers' Association; 2009.
[33] Meier AK. Refrigerator energy use in the laboratory and in the field. Energy Build 1995;22:233–43.

[34] Sidler O, Waide P, Lebot B. An experimental investigation of cooking, refrigeration and drying end-uses in 100 households. Asilomar (California): ACEEE (American Council for an Energy Efficient Economy); 2000. p. 1–285 to 1–94.
[35] Zimmermann J-P, Evans M, Griggs J, King N, Harding L, Roberts P, et al. Household electricity survey: a study of domestic electrical product usage in the UK. Milton Keynes (UK): Intertek Testing & Certification Ltd with Enertech (France); 2012. p. 600.
[36] Energy efficient strategies, Maia consulting. Energy standards and labelling programs throughout the world in 2013. Canberra: Department of Industry; 2014.
[37] Bansal P, Fothergill D, Fernandes R. Thermal analysis of the defrost cycle in a domestic freezer. Int J Refrig 2010;33:589–99.
[38] Bansal PK, Chin TC. Design and modelling of hot-wall condensers in domestic refrigerators. Appl Therm Eng 2002;22:1601–17.
[39] Bassiouny R. Evaluating the effect of the space surrounding the condenser of a household refrigerator. Int J Refrig 2009;32:1645–56.
[40] Gupta JK, Ram Gopal M. Modeling of hot-wall condensers for domestic refrigerators. Int J Refrig 2008;31:979–88.
[41] Stoecker WF, Jones JW. Refrigeration and air conditioning. 2nd ed. New York: McGraw-Hill; 1982.
[42] Embraco. Model EG AS70HLP; 2014.
[43] Embraco. Compressor performance maps; 2014.
[44] Australian Consumers' Association. Raw test data for household refrigerators and freezers. Choice. 1999–2012 ed. Sydney: Australian Consumers' Association; 2012.
[45] AS/NZS4474.1. Performance of household electrical appliances—Refrigerating appliances: Part 1: Energy consumption and performance. Sydney: Standards Australia; 2007.
[46] Klein SA. Engineering equation solver. V10.212 ed: F-Chart Software; 2017.
[47] Harrington L, Aye L, Fuller R. Opening the door on refrigerator energy consumption: quantifying the key drivers in the home. Energy Effic [submitted for publication].
[48] Harrington L. Quantifying energy savings from replacement of old refrigerators. Energy Procedia 2017;121:49–56.
[49] Sustainability Victoria. Refrigerator retrofit trial. Melbourne; 2017.
[50] Coulter WH, Bullard CW. An experimental analysis of cycling losses in domestic refrigerator-freezers. Air Conditioning and Refrigeration Center, University of Illinois at Urbana-Champaign; 1995.
[51] Rubas PJ, Bullard CW. Assessment of factors contributing to refrigerator cycling losses. Air Conditioning and Refrigeration Center, University of Illinois at Urbana-Champaign; 1993.
[52] Dubba SK, Kumar R. Flow of refrigerants through capillary tubes: a state-of-the-art. Exp Therm Fluid Sci 2017;81:370–81.
[53] Bagarella G, Lazzarin RM, Lamanna B. Cycling losses in refrigeration equipment: an experimental evaluation. Int J Refrig 2013;36:2111–8.
[54] Rubas PJ, Bullard CW. Factors contributing to refrigerator cycling losses. Int J Refrig 1995;18:168–76.
[55] Janssen MJP, de Wit JA, Kuijpers LJM. Cycling losses in domestic appliances: an experimental and theoretical analysis. Int J Refrig 1992;15:152–8.
[56] Björk E, Palm B. Refrigerant mass charge distribution in a domestic refrigerator, Part I: Transient conditions. Appl Therm Eng 2006;26:829–37.
[57] Boeng J, Melo C. Mapping the energy consumption of household refrigerators by varying the refrigerant charge and the expansion restriction. Int J Refrig 2014;41:37–44.
[58] McGill I. Trends in refrigerator designs and operational issues. In: Personal communication with the author. Senior refrigeration design engineer. Fisher & Paykel Appliances; 26 September 2014.
[59] Energy Efficient Strategies. Whitegoods efficiency trends in Australia 1993–2014. Canberra: Department of Innovation, Industry and Science; 2016.
[60] Weiss M, Patel MK, Junginger M, Blok K. Analyzing price and efficiency dynamics of large appliances with the experience curve approach. Energy Policy. 2010;38:770–83.
[61] Harrington L, Aye L, Fuller R. Energy impacts of defrosting in household refrigerators: lessons from field and laboratory measurements. Int J Refrig [submitted for publication].
[62] Harrington L, Aye L, Fuller R. Characterising indoor air temperature and humidity in Australian homes. Air Qual Clim Change 2015;49:21.